




Article

High Current Measurement of Commercial REBCO Tapes in Liquid Helium: Experimental Challenges and Solutions

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Abstract: Recent advances in high-temperature superconductors (HTS) have made them extremely attractive for low-temperature, high-magnetic-field-power applications such as in fusion technology, where the advantages over traditional low-temperature superconductors (LTS) allow for the design of fusion reactors operating in different and more convenient regimes. However, the performance enhancement exhibited by novel conductors poses several challenges for the measurement of their superconducting properties. The high critical currents coupled with the relatively low thermal stability of the conductors and their mechanical fragility render this task a challenge, as the angular anisotropies complicate the experimental setup. In this work, we describe the development of our novel high-current measurement facility, focusing on the solutions introduced regarding critical aspects such as the superconducting leads and the sample holder design. We show how simple but effectively designed solutions can be adopted to combat the complexity of the measurement. The results reported in this work guide the development of a measurement system able to withstand high critical currents ($I > 1500$ A) at high magnetic fields ($\mu_0 H > 12$ T) by evaluating the angular response of 4 mm wide short samples ($L \sim 7.5$ cm) in a robust and reproducible manner.

Keywords: REBCO; coated conductor; critical current; angular behavior

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Citation: Masi, A.; Freda, R.; Formichetti, A.; Greco, A.; Alimenti, A.; Khan, M.R.; Celentano, G. High Current Measurement of Commercial REBCO Tapes in Liquid Helium: Experimental Challenges and Solutions. *Appl. Sci.* **2024**, *14*, 7697. <https://doi.org/10.3390/app14177697>

Academic Editor: Roberta Sparvoli

Received: 2 August 2024

Revised: 23 August 2024

Accepted: 28 August 2024

Published: 31 August 2024



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1. Introduction

Recent advances in the technological application of high-temperature superconductors (HTS) [1] are based on the concept of a coated conductor, a strong metallic substrate (e.g., nickel and iron alloys) that supports a superconducting film deposited epitaxially on a buffer layer and protected via the application of a conductive metal (e.g., silver or copper). The different processes involved in the realization of a CC and the different architectures possible in terms of buffer layer structure and materials involved lead to a vast outcome concerning the characteristics of the tapes. The different productive choices influence the superconducting properties, such as the critical temperature and the magnetic field and angular behaviors of the superconducting currents, which are highly dependent on the crystalline microstructure. In this framework, i.e., the increase in commercial CC production driven by fusion applications [2] and the enhancement of their performance, a solid benchmark platform is necessary to be able to measure their properties in the operating conditions of superconductivity laboratories that operate with such conductors. To fully characterize and validate the tapes' properties, experimental facilities able to deliver large amounts of current (e.g., $I > 1000$ A) at high magnetic fields ($\mu_0 H > 12$ T) performing measurements at different angular configurations are, in fact, required. This is required in order to support the optimization of the production process so that industries

are able to tailor the CCs' properties for applications to achieve the best performance for the development of cables and coils.

In this work, we report our findings regarding the development of a simple but effective high-current probe. The probe is designed to work in liquid helium bath, includes HTS leads in order to minimize both helium evaporation and thermal transfer to the sample, and is conceptualized to allow a modular sample-holder design comprising an angular measurement sample holder. To the best of our knowledge, not many groups perform angular measurements of REBCO-coated conductors on full 4 mm tapes at liquid helium temperature (e.g., [3–5]). This work thus represents a useful guide to approaching and solving the experimental problems that can arise in this kind of challenging measurement. The work addresses several aspects, such as the production of simple and effective current leads, the design of different sample holders, and the adoption of different sample mounting strategies and soldering alloys, and reports a comparison of the results obtained for different samples in different conditions.

2. Superconducting Current Leads Development

The set-up of a high current probe necessitates some compromise, needing to balance the different heat loads to the sample and the bath due to joule heating and thermal transfer from room temperature. The experimental apparatus utilized for high-current measurements of wires and tapes in our laboratory is based on a cryostat that encases a 14 T magnet with a useful bore 80 mm in diameter operating in a liquid helium bath. The liquid helium bath is shared with the sample, and this renders the efficient use of the cryogenic liquid (i.e., avoiding unnecessary consumption) of the utmost importance in order to safely operate the magnet while carrying out the measurements. For this reason, we decided to adopt the hybrid resistive-superconducting approach.

We decided to avoid multiple sectioning of the current probe, keeping a simple design. The resistive part of the measurement probe is based on OFHC copper current leads (copper wires, 250 mm² total section for each lead) insulated between them and inserted into a steel tube. The resistive part is cooled through evaporation of liquid helium vapors. The length of the superconducting leads was chosen as the minimum needed to avoid the immersion of the resistive leads in the liquid helium bath. In our magnet, this corresponded to approximately 55 cm of length between the sample and the resistive portion. A 45 cm L-shaped stainless steel (0.4 mm thick) part was chosen as the mechanical support and brazed at the ends to copper terminals 20 mm wide and 10 mm thick. REBCO HTS tapes could be then allocated onto the flat 20 mm portion of the support, coupling eight tapes in four pairs on each lead, as shown in Figure 1.

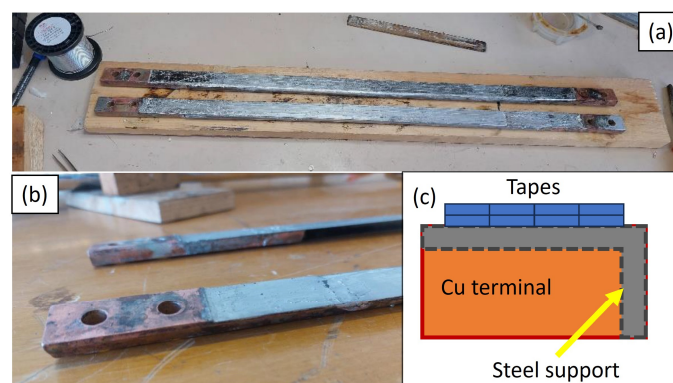


Figure 1. Superconducting leads after the soldering process (a) with details of the copper terminals (b) and schematic illustration of the current leads' cross-section describing the placement of the tapes on the top of the steel support and copper terminals (c).

Regarding the choice of the tapes, we chose tapes produced by SuNAM Co., Ltd. (Anseong-si, Republic of Korea) It is well known that SuNAM tapes are highly efficient at

high temperatures rather than being optimized for low-temperature–high-field conditions. This controversial choice to produce a low-temperature–high-field measurement apparatus was based on two factors:

1. SuNAM tapes are characterized by higher robustness thanks to the stainless steel substrate with respect to better-performing recent tapes that include Artificial Pinning Centers (APCs) to increase the critical current. This becomes useful when considering mechanical stresses induced by the thermal strain arising from the different materials and interfaces.
2. Failure of the superconducting section would, in our opinion, most likely be driven by thermal factors at the warmer end rather than lack of performance in the liquid helium bath, as is later discussed in the text.

Previous experiments were also carried out with tapes from different producers, utilizing a brass support rather than the steel one. However, despite some positive factors—such as an easier soldering step for brass—the difference in thermal contractions led to failures due to the delamination of tapes and detachment at the copper terminals following thermal cycling. The final chosen configuration (SUNAM on steel support) demonstrated its robustness through several tens of thermal cycles, with no evidence of degradation or quenches.

The superconducting leads after the soldering process are shown in Figure 1. As previously introduced, four pairs of tapes were aligned on the surface of the copper terminals and on the steel support, with the REBCO side towards the metal. The inner tape was cut 10 mm shorter than the outer tape to allow for direct contact of the latter with the copper terminals and to optimize the current redistribution. To protect the extremities, a thin copper foil was placed above the stack in correspondence to their ends. A low-melting-point soldering alloy (In-Sn) was used for the soldering to minimize the thermal stress on the tapes.

To assess the effectiveness of the production step and evaluate the performance of the current leads, these were tested in liquid nitrogen. The results following the subtraction of a linear contribution ascribable to the redistribution of the current at the copper terminals due to the close voltage placement are shown in Figure 2. A rapid voltage rise can be observed above 1500 A, demonstrating the occurrence of a superconducting transition. The critical current was estimated by fitting the experimental curves with a linear contribution over the imposed $\left(\frac{I}{I_c}\right)^N$ formula (1 $\mu\text{V}/\text{cm}$ criterium), resulting in values close to 1750 A for both leads. These results suggest good homogeneity between the two samples and, most importantly, values in line with the expected ones, with approximately 220 A per single tape, as measured in the self-field in liquid nitrogen.

The assembled high-current probe is reported in Figure 3, which shows the steel tube covering the resistive leads and the HTS part with a mounted sample holder. For practical use, to protect from potential impacts and to vehiculate helium vapors inside the tubing, during the measurements, the HTS leads are surrounded by a thin G10 high-pressure fiberglass laminate tube, which is not shown here in the picture. During the measurements of the HTS samples, the status of the superconducting leads was assessed by means of voltage measurements carried out along their length, with no evidence of quenches of the superconducting portion occurring at the highest currents and fields. The helium consumption from the bath was drastically reduced following the introduction of the HTS part. While a single measurement run could be performed with the resistive lead, due to both the serious helium consumption during the probe cooling and to the heat leak caused by the large copper area, several samples (i.e., cooling and heating of the probe and high current measurements) could then be measured with the same helium amount.

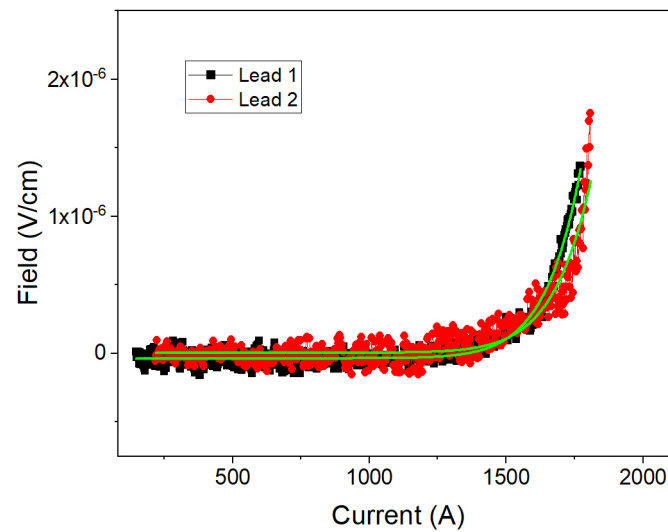


Figure 2. Voltage–current curves measured for the HTS leads in LN₂ (black and red points), with overimposed critical current fit (green curves) for 40 cm far voltage taps.

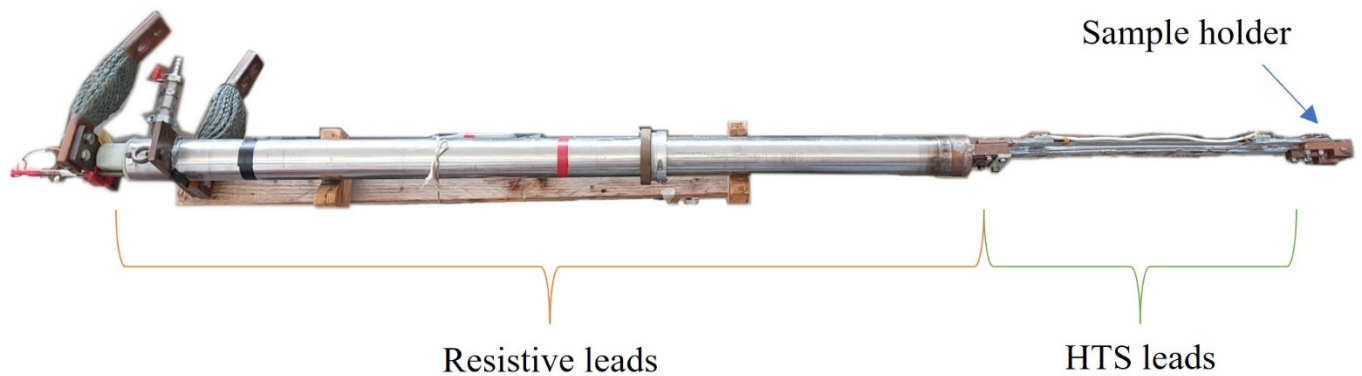


Figure 3. Picture of the assembled high-current probe.

3. Sample Holder Design

The sample holder can play a crucial role concerning the measurement, having to provide a current to the sample while granting mechanical support without influencing the tape's performance. The interface between the sample and the current leads could be under pressure or soldered, depending on the design (e.g., [3] or [6]). While a pressure contact carries a higher level of simplicity during sample mounting procedures and avoids thermal treatments that could ruin the sample, soldering grants higher stability and lower contact resistance. To pursue higher efficiency and robustness, in our laboratory, we decided to select the soldering approach.

We designed and tested several sample holders characterized by differences in the sample placement concept and in the supporting material. Some descriptive drawings are reported in Figure 4.

- The sample holder in the panel (a) is constituted by a G10 board with a 4 mm large groove, which is rounded towards the edges with a flat section where the field is perpendicular to the tapes. It accommodates approximately 25–30 cm of tape, with 10 cm in the G10 portion and 3 cm in the flat part where the primary voltage taps are placed. This design, partially inspired by previous works of Tsuchiya et al. [6,7], is characterized by a good section of copper devoted to the sample soldering, but relies mostly on the groove and on the sample's pre-tension to support the tape.
- The sample holder in panel (b) is constituted by a steel support bent and brazed on the copper terminals. The tape dimensions are similar to those obtained in the G10

support. This design preserves a large soldering surface and introduces a metallic support where the tape can be soldered along its entire length, enhancing mechanical support and granting good thermal stability for the sample.

- The design in panel (c) relies instead on a flat steel support that is soldered simultaneously with the tape on the flat extremities of copper terminals. The sample length is limited to approximately 7.5 cm due to the bore size. It is characterized by extreme simplicity in the sample mounting, but reduces the soldering length to the length of side of the copper support (i.e., 25 mm in our case) and limits the dimension of the center part where the voltage probes are accommodated.
- The design in panel (d) describes an angular measurement option. The sample holder exploits the flat approach, and the tape is soldered inside a groove obtained on a round support for its entire length of approximately 7.5 cm. This support is composed of copper extremities (i.e., 25 mm) and a central steel portion. The copper extremities are eventually clamped onto the copper terminals.

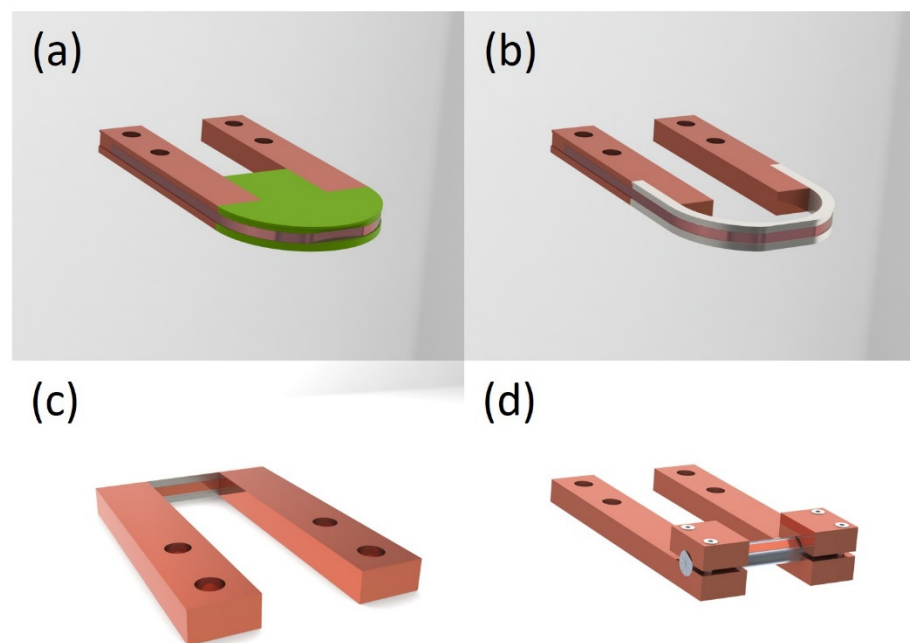


Figure 4. Drawings of the tapes' sample holders: (a) G10, (b) curved steel, (c) flat steel, (d) angular.

The first difference between these supports is the length and the shape that the tape will assume, i.e., whether the tape will be bent or will remain flat. This has consequences for the field/tape orientation along the whole sample, both on the soldering area and on the probed lengths.

Regarding the first aspect, a curved sample introduces a weak section into the tape, i.e., a section where the critical current is lower with respect to the other sample parts, localizing the transition. This should, in principle, correspond to the area where the field is perpendicular to the surface, i.e., the central part, due to the anisotropy of the REBCO superconducting properties. In this case, the transition would be far from the soldered part and should be less influenced by the thermal phenomena occurring there. The bending step, however, should be always carried out carefully. As was previously reported to be critical for the measurement's reproducibility [7], we also observed a critical role of the sample mounting step, which was more associated with the mechanical handling of the tapes rather than with other phases.

On the contrary, a flat sample is easier to handle. For size constraints, however, its length is limited by the bore size, leading to a compromise between the soldering area and free section. Perturbation due to thermal effects at the terminals could potentially be

enhanced due to the short lengths, and localization of the transition driven by the tape anisotropy is not possible.

A second difference is the material of the support. The choice between a G10 support or a metallic fixture influences both the mechanical coupling and the presence of an electrical and thermal stabilizer. A G10 support, for example, has a limited role, both in keeping the tape mechanically stable when subjected to extremely high Lorentz forces and in preventing the tape from heating following the transition, potentially leading to burning of the tape. This is particularly true for the last generation of commercial tapes, which had low, thin mechanical stabilizers (e.g., 50 μm thick Hastelloy). An example of such an occurrence is reported in Figure 5, which shows a tape irreversibly damaged after a quench event occurring few amperes above the critical current (voltage criteria were exceeded by only a factor of 2).



Figure 5. Picture of a REBCO tape mounted onto the G10 sample holder after a quench event, showing discoloration and evident mechanical deformation (red circle) caused by hot-spot development that led to irreversible degradation.

When delivering large amounts of currents in high magnetic fields, Lorentz forces are, in fact, a factor that needs to be accounted for. Although, in the current leads, the current flows parallel to the magnetic field, thus exerting no net force, in the sections where the field and the current path are perpendicular, large transversal forces act on the system. In the worst case (i.e., high fields and high currents), forces on the order of hundreds of N are applied onto the few cm of the tape perpendicular to the field. The soldering of the tape on the metallic sample holders allows these stresses to be transferred onto the support, allowing for stable measurements thanks to the more robust configuration.

The presence of a large electrical stabilizer could, however, influence the measure if the current is not injected efficiently into the superconductor. The presence of a non-insulating fixture, in fact, provides a parallel path for the currents. The amount that flows into the stabilizer is eventually driven by the relative ratio of the metal resistance and contact resistances, which play a major role in current redistribution. With our different set-ups and configurations, however, we did not observe a significant perturbation induced by this factor. Figure 6 depicts IV curves obtained for samples of the same batch of tape (from Shanghai Technologies) mounted on different sample holders. Apart from a small spread in critical currents varying between 165 A and 175 A, potentially due to small inhomogeneities in the sample batch, no significant differences can be observed on the transition shape or N values, which are close to 30 for all the samples.

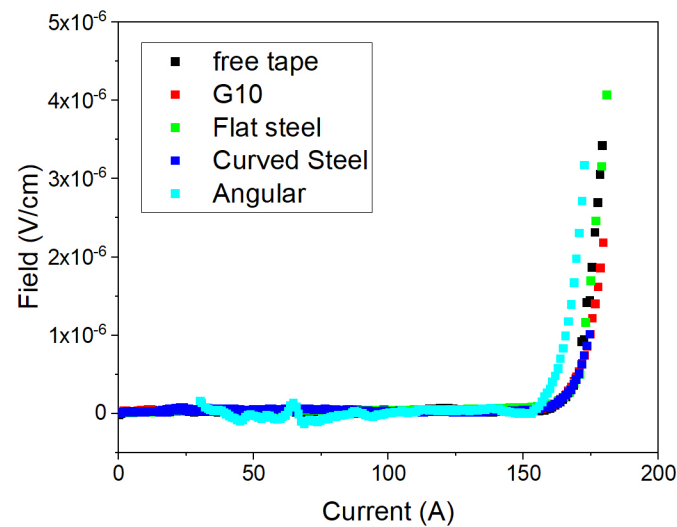


Figure 6. Field/current curves obtained for samples of the same Shanghai Technologies tape on the different sample holders in LN₂. A linear contribution has been subtracted from the curve related to the angular sample holder (see text for details).

The sample holder design and current flow path can, however, affect the measurement if the voltage taps are placed so as to take into account resistive voltages due to interfaces or resistive portions of the circuit. In an ideal experiment, in fact, voltage taps should be placed onto the tape surface, insulated from the rest of the experimental set-up. When adopting a metallic fixture, however, this may not be always possible. In our angular design, for example, as highlighted in Figure 7, the tape is inserted into a slot carved into the round support and soldered along its length.

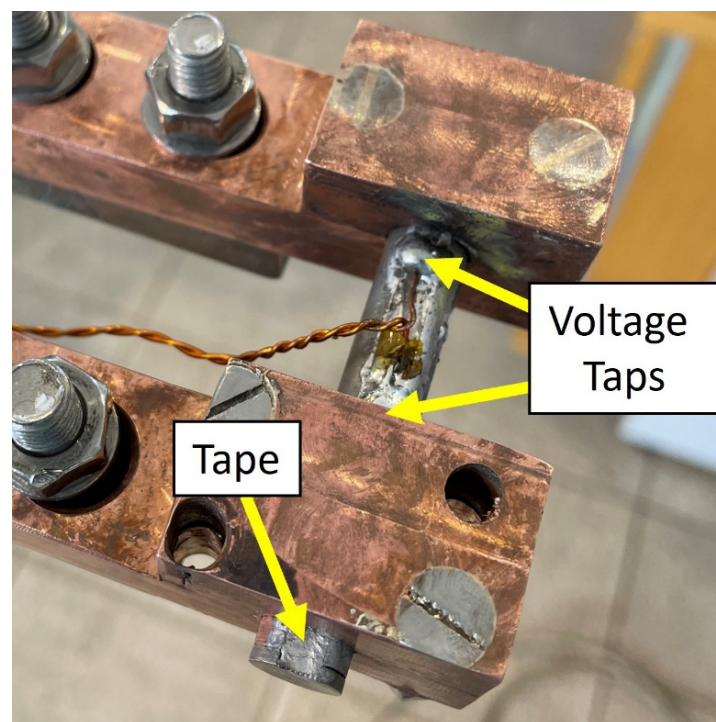


Figure 7. Detailed picture of the angular sample holder, with the tape mounted inside the slot in the support oriented in order to obtain the magnetic field parallel to the tape surface. The positions of the voltage taps are highlighted.

Current transfer occurs from the copper terminals to the round support, and is only then redistributed to the tape. Voltage taps embedded in the solder are likely to also collect transverse voltages due to current redistribution inside the sample holder, leading to resistive slopes before the superconducting transition.

This is represented in Figure 8, where the characterization of a Shanghai Technologies tape mounted onto an angular sample holder, carried out in liquid helium at different magnetic fields parallel to the tape surface, is shown. It can be observed that all curves are characterized by resistive behavior up to a high current before the superconducting transition. After subtraction of this linear background, IV curves characterized by good signal-to-noise ratios are obtained. The increase in the linear coefficient with the increasing field is qualitatively consistent with an increase in interface resistance when the magnetic field is applied.

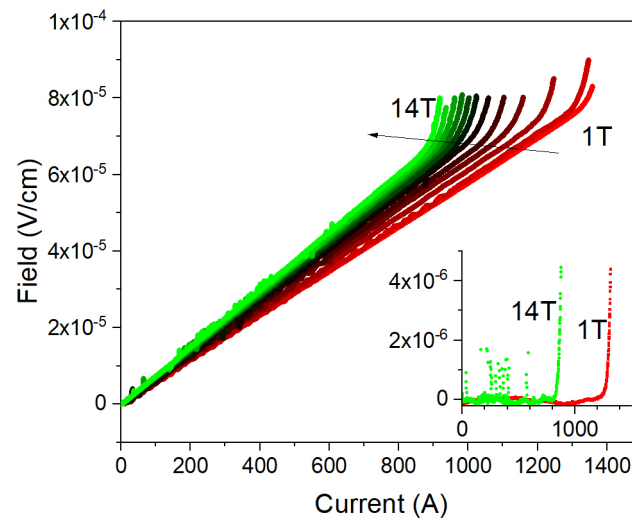


Figure 8. Field/current curves acquired at 4.2 K for a Shanghai Technologies tape on the angular sample holder with the field parallel to the tape surface at various magnetic fields. In the inset, the 14 T and 1 T curves after subtraction of a linear background are represented to enhance the superconducting transition.

In this sense, in our experiments, this spurious contribution did not lead to anomalies in the results, and the amount of extra work needed to analyze the results (e.g., additional fitting) was worth the simplicity that characterized the sample holder's design.

4. Soldering and Sample Mounting

The contact electrical resistance, and, thus, the development of heat due to ohmic heating, could have affected both measurement reliability (due to heat propagation) and efficiency (due to helium evaporation and consumption). This factor is directly related to the effectiveness of the soldering process. We evaluated different traditional low-melting-point soldering alloys, such as Bi-Sn, Pb-Sn, and In-Sn. Focusing on the last two, while Pb-Sn was characterized by higher mechanical and electrical properties, the latter exhibited a lower melting point (approx. 120 °C vs. 190 °C), which could represent a significant advantage in terms of avoiding sample degradation due to thermal factors [8].

To assess the difference in contact resistance due to two soldering alloys, we carried out resistance measurement in a liquid nitrogen bath comparing couples of superconducting tapes soldered among them with different alloys. We obtained values of the inter-tape electrical resistance close to $50 \text{ n}\Omega \cdot \text{cm}^2$ in both cases. Rather than focusing on the absolute value, which may be influenced by several factors ascribable to the nature of the tape surface due to its manufacturing [9], we observed a 20% difference in favor of the Pb-Sn alloys, which exhibited lower values. We decided that the processing ease due to the melting temperature gain was more favorable than the enhancement in the electrical properties and

adopted the In-Sn alloy as the standard to prepare the samples. During the critical current measurement, we routinely evaluated the contact resistance by measuring the voltage drops across the soldered junctions, i.e., between the tape and the sample holder or the resistive leads. These values obviously also need to take into account the contribution due to the resistive element. However, resistance values on the order of 100 nΩ were commonly observed at liquid nitrogen temperatures, scaling well with the soldered area. This is coherent with the consideration that the main variable in play was the length of the tape soldered to the support. A drop of 30–50% was commonly observed in the liquid helium bath, allowing us to foresee heating due to joule effects in the range of tens/hundreds of mW at high currents.

The obtained resistance values do not seem to represent an issue for measurements carried out in liquid helium baths, not even in the case of the flat sample holders characterized by shorter soldering areas and, thus, higher resistance. In Figure 9, we show a comparison of different measurements carried out on samples of Shanghai Technologies tapes mounted on different sample holders at different fields. It can be observed that no significant differences arose due to the fixture, either at high fields where the field orientation and transition localization could play a role in the mechanical stability or at lower fields where higher currents could lead to heating phenomena on shorter samples.

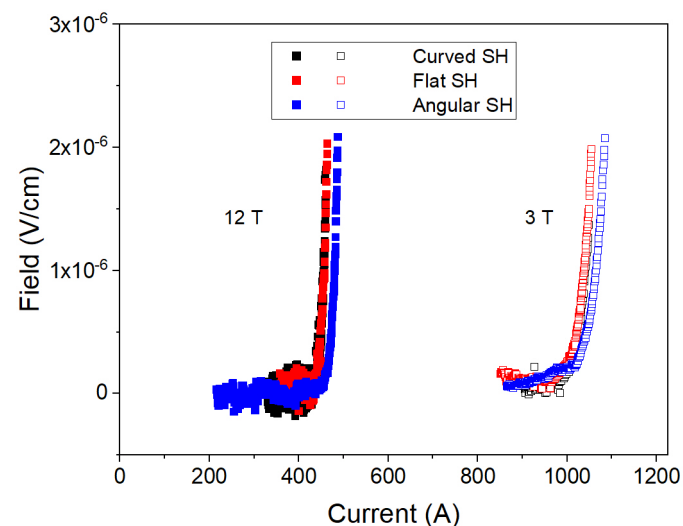


Figure 9. Field–current curves measured for a Shanghai Technologies tape at high fields and low fields mounted on different sample holders (field perpendicular to the surface).

It is worth highlighting that, already, the sample holder with the simplest design, i.e., the flat sample holder, which was characterized by ease of mounting and not needing long samples, was able to deliver good measurements characterized by a good SNR ratio in our experimental set-up. We take this factor as an indicator of the quality of the measurement, considering its dependence on several factors such as the tape’s mechanical stability, the length of the probed region, and the voltage wires’ stiffness. To achieve these results, some trial and error was also conducted on voltage tap wires, looking for the best compromise between wire thickness and rigidity, and eventually, the adoption of shielded wires for the upper sections of the voltage leads. In Figure 10, we show the field–current curves measured at high fields for a Shanghai Technology tape mounted on the flat sample holder. It can be observed how, despite the performance of the tape and, thus, the high electromagnetic forces and potential heating phenomena involved, smooth field–current curves were acquired with no evidence of instability.

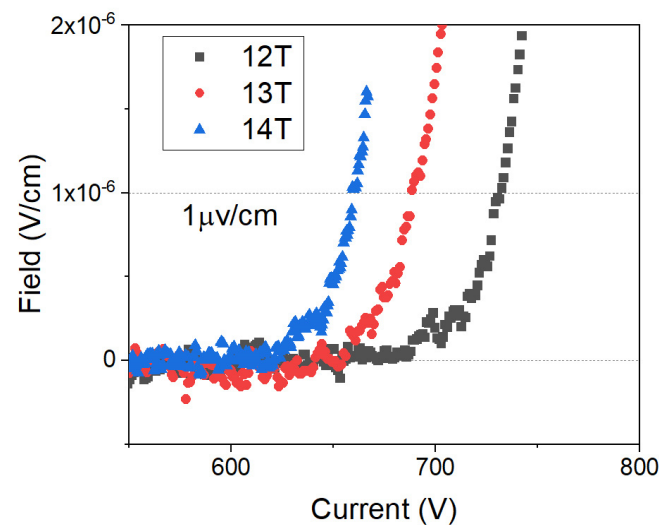


Figure 10. Field–current curves for a Shanghai Technologies tape at different magnetic fields measured with a flat sample holder.

5. Angular Measurements

Further insight is now provided into the measurements carried out with the angular sample holder. Considering the possibility of measuring tapes at fixed angles, without the complexity introduced by an in situ angular movement system [5], different sample holder concepts could have been developed, such as variations in the flat concept at different fixed angles, as introduced by Barth et al. [3]. This design, however, either relies on pressure contacts or needs to take into account the high-temperature de-soldering, removal, and movement of the sample into a new position, or the use of a different sample for every angular measurement. Instead, we designed our clamping design to be able to carry out different measurements in the whole angular range on the same soldered sample without further thermal treatments other than the first one, as previously reported for measurements carried out in liquid nitrogen [10]. This does not come without a price, however: the adoption of the round clamping system brings about uncertainty in the measured angle, which we estimated as $\pm 5^\circ$, and requires repeated heating and cooling runs for different angles. The issues introduced by several cooling and heating cycles are mitigated by the limited helium consumption achieved with the new current probe, and these drawbacks were considered as minor issues when facing the robustness of the set-up; we are sure that differences in the measurement were only due to the angular contribution.

In Figure 11, we show the results of the critical current measurements for a SuNAM tape at different angles and fields. It can be observed how the critical current was raised sensibly when approaching the condition with the field parallel to the ab planes, with the effect being much more pronounced at higher fields, where a ~ 7 -fold increase is shown between the perpendicular and parallel condition. The N-index, the exponent of the fit of the superconducting transition following the well-known $\left(\frac{I}{I_c}\right)^N$ formula, was evaluated in the $0.1\text{--}1\ \mu\text{V}/\text{cm}$ range, showing similar values for angles in the $0\text{--}70^\circ$ range and increasing instead at 90° .

Figure 12 instead depicts the results of the angular measurements for a Shanghai Technology tape. It is clear how the introduction of APC mitigates the loss of critical current with the field perpendicular to the tape surface with respect to the parallel scenario. Furthermore, the measurement highlights a similar angular behavior to that observed for similar tapes at higher temperatures and lower fields [11], suggesting that the pinning landscape exhibited at high temperatures and low fields is also effective at lower temperatures and higher fields. n -index values seem to exhibit a decreasing trend when moving from the field perpendicular to the surface to parallel to the ab planes.

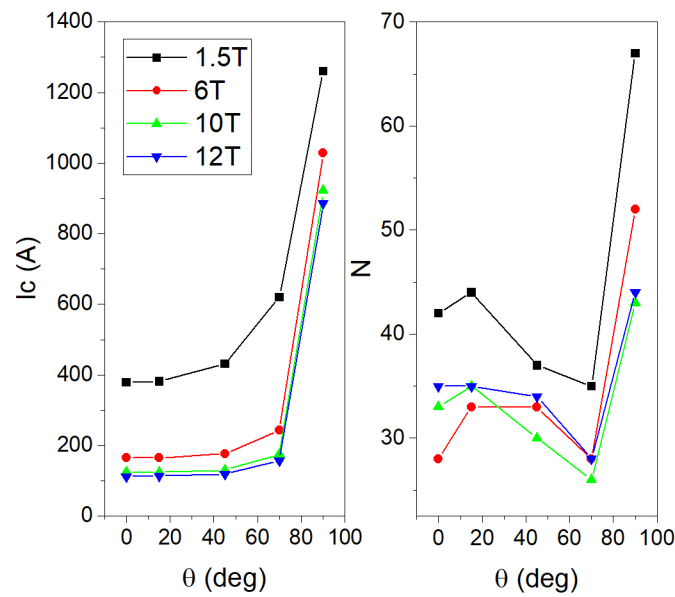


Figure 11. Results of angular measurements (I_c and N-index values) for a SuNAM sample at different fields at 4.2 K.

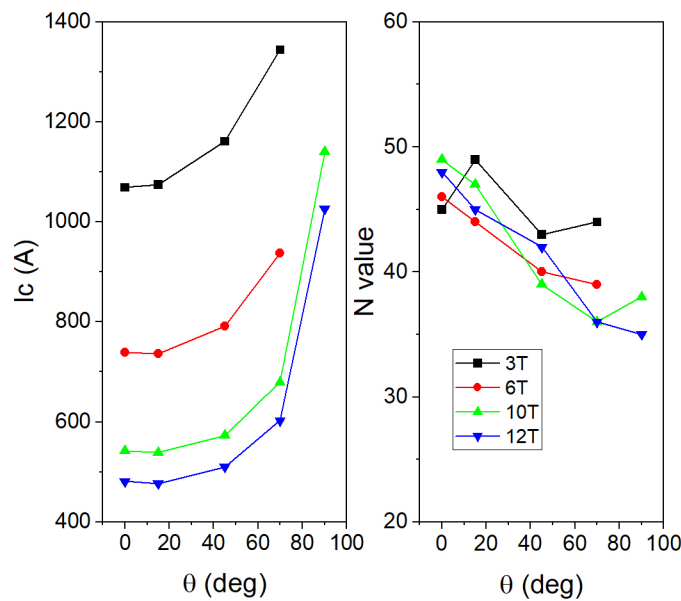


Figure 12. Results of the angular measurements (I_c and N-index values) for a Shanghai Technologies sample at different fields at 4.2 K.

The comparison of the two tapes shown here confirms the consideration we put forth in the first section about the choice of SuNAM tapes for the application of current leads in a liquid helium environment. Despite the low critical current value (around 100 A at maximum fields) with fields perpendicular to the tape, the critical current when the field was parallel to the tape was, in fact, significantly enhanced in the SuNAM sample due to its intrinsic pinning landscape. The current leads, in our design, work with the field always parallel to the surface, granting us a significant theoretical current margin in operating conditions. Qualitatively analyzing this aspect, in fact, if we were to consider the performance of the probe to be limited only by the high-field performance of the eight tapes, we would be limited to an astonishingly high value of 7 kA, well above the acceptable load of the resistive part.

6. Conclusions

Recent advances in coated conductor production have led to novel products characterized by extremely high critical currents at low temperatures and high magnetic fields, allowing for the design of fusion machines based on such conductors.

The anisotropy of the material and of the product, however, coupled with their high performance, establishes challenges for their characterization and qualification. In this work, we show our recent work related to the set-up of a measurement facility for REBCO tapes. We report the production of simple and effective superconducting current leads which are effective in reducing the evaporation of liquid helium baths with respect to fully resistive probes and reducing the thermal transfer to the sample. The leads show resistance towards thermal and electromechanical cycling and exhibit a performance in line with what was expected following the design phase.

Furthermore, we show and compare different sample holder designs, characterized by different strengths and drawbacks, which are able to deliver robust performances at high fields up to the current limits of our facility (i.e., 1500 A). Moreover, a sample holder for angular measurement is developed and tested, allowing us to measure consistently through the whole angular range up to high fields and high currents. Future work will be devoted towards the enhancement of the facility capability, particularly in terms of the maximum deliverable current, with ongoing plans to expand the power supply set-up above 2 kA.

Author Contributions: Conceptualization, A.M. and G.C.; methodology, A.M.; validation, A.M.; formal analysis, A.G., A.A. and M.R.K.; investigation, A.M., A.G. and M.R.K.; resources, R.F. and A.F.; writing—original draft preparation, A.M. and G.C.; writing—review and editing, A.M.; visualization, A.M. and A.F.; project administration, G.C.; funding acquisition, G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been partially carried out within the framework of the EUROfusion Consortium funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200—EUROfusion). The views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This work was partially supported by the Italian National Operational Programme (PON) on Research and Innovation 2014-2020—Action IV.6 (PON project 999900_PON_RTD_A7-G-999_INGEGNERIA_IEM).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank F. Maierna, M. Marchetti, and L. Merli for their precious assistance.

Conflicts of Interest: Author Andrea Formichetti was employed by the company ICAS Srl. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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